Infection of Air*

Bacteriologic and Epidemiologic Factors

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CONCENTRATION of microörganisms in air (the number dispersed in unit volume) implies some degree of confinement. The potential hazard of infection from the air breathed in the semi-confined spaces of our habitations may be represented for any moment in time by the equilibrium between the addition rate of microörganisms and the rate of their elimination. A bacteriologic technic for the measurement of sanitary ventilation, inversely determining confinement, has been previously described.[1] The rate (K) at which bacteria suspended in semi-confined atmospheres are vented or killed may be determined directly, and changes in ventilation rates may be computed from the formula $P=C/K$ where the equilibrium (P) is measured and the rate of addition (C) of bacteria is maintained constant.

CONFINEMENT OF AIR-BORNE MICROÖRGANISMS

If air displacement alone in ventilated rooms is to be measured, no advantages are claimed for bacteriologic procedures over gasometric methods.† In measuring infection and disinfection of air, however, the bacteriologic procedure offers a means of interpreting biologic ventilation in terms of air replacement. The rate at which viable microörganisms disappear from a semi-enclosed atmosphere through physical, chemical, or biological means can be expressed as equivalent ventilation (based upon air replacement).

The importance of distinguishing between the hygienic potentialities of bacterial ventilation by air displacement and by other means of disinfecting habited atmospheres has become evident from analysis of some 1,750 air samples, collected in studies on sanitary ventilation to be reported later. During the winter months, associated

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† The equilibrium formula applies equally well if CO_2 is added to a room at a known constant rate (C). Let the rate of addition of CO_2 per person per hour (C) be 0.5 cu. ft.[2] With an air space of 200 cu. ft. per person,[3] the addition rate $(C) = 0.5/200 = 0.0025$ volumes per hour. With an air replacement of 1,200 cu. ft. per person per hour,[3] the removal rate $(K) = 1{,}200/200$ or 6 overturns per hour. The equilibrium (C/K) will be 0.0025/6 or 4.2 volumes of CO_2 per 10,000 volumes of air. With an outside concentration of between 3 and 4 volumes per 10,000 the inside concentration would lie between 7 and 8 volumes. "Pettenkofer, in 1858, proposed 10 volumes of carbon dioxide in 10,000 volumes of air as a limit for inhabited rooms. DeChaumont (1875) found that an unpleasant odor became perceptible in air containing 6 volumes of carbon dioxide in 10,000, and fixed this as a limit, which for many years was accepted by sanitarians." [2]

with the spread of respiratory infections, when the closing of doors, windows, or other natural vents confines the air commonly breathed by many persons, natural ventilation rates fall below 10 overturns per hour. To double air replacements, during cold weather, by mechanical or window ventilation raises practical difficulties, and has led to no conspicuous decline in respiratory diseases. With the opening of windows in the spring such infections consistently decline, with ventilation rates approaching 100 overturns per hour. Whether equivalent bacterial ventilation by air disinfection during the winter can accomplish similar hygienic results is an important problem in sanitary science.

An example of the solution of a general problem of sanitary ventilation by means of air disinfection, through experimental methods applying the bacteriologic procedure, is provided in the study and design of isolation cubicles in which ultra-violet light screens replace solid partitions or in which there is dropped a curtain of light continuous with an irradiated reservoir or " ceiling " above the eye level into which any solid cubicle partitions project.[4] Such cubicles, the experimental units of which were built and tested in the Henry Phipps Institute, Philadelphia, are now in routine use in the new building of the Cradle Society, Evanston, Ill. (Figure I). Sanitary ventilation tests upon the bacterial tightness of the experimental cubicles indicated: (1) in Type A cubicles (i.e., with solid partitions between cubicles, ultra-violet light curtains between cubicles and corridor), 99.6 per cent of the test organisms were removed in passing from the corridor to the cubicle, 98.9 per cent in passing from the cubicle to the corridor; (2) in Type B cubicles (i.e., where partitions between cubicles also were replaced with a curtain of ultra-violet light), 99.7 per cent of the test organisms were removed in passing from cubicle to cubicle. Tests upon the cubicles in the completed building, under actual operating conditions, have exceeded the results in the experimental unit.

Trial installations of light barriers have also been designed for the Children's Hospital, Philadelphia, and the Infants' and Children's Hospital, Boston, and such cubicle isolation would seem generally applicable to hospital use.

BACTERIOLOGIC FACTORS

Methods—The equilibrium between the infection rate and the ventilation rate of the air of our habitations varies with a multitude of factors such as season, weather, variations in activity from day to day, hour to hour, or even minute to minute. The statistical constants which define these variable characteristics depend upon the analysis of numerous samples and, since air is a rarefied medium, upon large volumes. Examination of so changeable a medium requires an instrument adaptable to extensive field service. Simplicity and directness in technic are practical prerequisites both of economy and accuracy in any widespread sanitary survey.

It goes without saying that a method must be determinate, that with each condition a definite result is obtained, and that these results under uniform conditions are reproducible within the normal variation of the conditions themselves. It is a matter of convenience that the results be quantitatively proportionate to variations in conditions, or bear some simple functional relationship. " Absolute bacterial densities " are mere abstractions useful only in interpretation, and never delivered by bacteriologic technics.[5]

The numbers and kinds of organisms recovered from an air sample also depend upon the conditions of culture. An instrument must be flexible enough to permit the use of various culture media. Direct collection on the culture medium may be desirable with sensitive parasitic organisms which quickly perish in the air. Organisms growing readily at blood temperature have been found in sanitary water analysis to be more indicative of pollution than those growing at room temperature, and the same principle holds in sanitary air analysis.[5] Whereas intestinal organisms are of primary concern in drinking water, nasopharyngeal organisms have significance in the air we breathe. Whereas gas formation in lactose broth is characteristic of intestinal contamination, green-producing streptococci (on blood agar) typify nasopharyngeal contamination. While special technic may be required in the search for pathogens or in special problems, the most serviceable method for general sanitary air analysis uses blood agar incubated at body temperature.

Results—Results of some two thousand air samples collected and analyzed by the Wells technic [6] are summarized in Table I. About one-third of these samples were analyzed in the authors' laboratories, with the assistance of several collaborators acknowledged in reporting the various studies. The remaining two-thirds of the samples were collected by the WPA Air Pollution Survey of the Department of Health of New York City,[7] and are indicated in the table by a dagger.

The textile mill samples represent atmospheres during a period of economic depression rather than the busy activity of better times. The average count given for Mental Hospital A does not give a complete picture for it averages the highest counts obtained under actual living conditions with lower counts which obscure this fact. The high streptococcus counts, however, may reflect the dissemination of respiratory organisms associated with the epidemic of pneumonia during which the samples were taken. The theater tests may also seem unnaturally low, and in the case of the Boston results we know the samples were taken between the warm and cold weather when the ventilating system was operating at its full capacity to exhaust the heat generated within the theater. In the results of subway samples as reported, there is nothing to indicate the jam during rush hours, nor does the report specify the conditions under which the samples were taken.

No pretense of precision can, therefore, be implied in this summary because standardization of collection and of isolation technics has not yet been perfected. Blurring due to imperfect technic may account for the want of contrast between some of the categories as compared to the clear definition observed among other categories. Want of technical skill in many of these laboratory analyses cannot be denied, any more than can perfect analysis compensate the failure of collections to represent truly their assumed classification—a more serious matter.

SANITARY INTERPRETATION

In spite of these imperfections, however, the categories exhibit significant differences which serve the primary purpose of this paper. The difference between the counts of indoor and outdoor air is outstanding. Most samples classed as "indoor air" were taken during the colder months when "indoor air" was "confined air." The mill samples, though collected during the summer, represent air confined in order to regulate the humidity.

Exclusion of Polluted Atmospheres—Particularly in hospitals, where pathogenic sources are known to exist; may high total count signify increased hazard of infection. The provision of independent air supplies in special wards or rooms (as the premature ward of the Infants' Hospital in Boston)[8, 9] where asepsis is a vital consideration

TABLE I

Sanitary Analyses of Air Supplies of Various Human Aggregations

	Number of Samples	Average Number of Colonies per Sample *	
		Total	Alpha Streptococci
Outdoor Air			
Boston, Longwood	72	16	0.12
Philadelphia, downtown	23	50	0.0
New York, streets †	143	112	0.45
New York, Central Park †	13	30	0.3
Outside various textile mills	14	46	0.0
Indoor Air			
I. Experimental			
Quiet	21	20	0.0
Sneezing	14	3,090	2,200.0
Empty after sneezing	4	1,440	920.0
Using handkerchiefs while sneezing	7	66	1.0
II. Hospitals			
Infants' and children's wards	160	496	0.8
Premature ward, separately air conditioned	26	20	0.0
Chapple incubator, separately air conditioned	92	18	0.0
Miscellaneous wards	13	247	2.9
Operating rooms			
During operations	6	450	...
Between operations	7	55	...
Children's out-clinics	28	728	13.3
III. Institutions			
Mental Hospital A, all wards	42	1,977	21.0
Mental Hospital B, senile ward			
Without ultra-violet lights	9	2,938	7.8
With ultra-violet lights	7	468	1.9
IV. Schools			
Public, New York †	707	296	1.8
Public, Watertown (Boston)	27	183	8.2
Private, Philadelphia	50	151	1.1
College laboratories and lecture rooms	22	106	1.4
V. Assemblies			
Theater, air conditioned, Boston	22	56	1.2
Theaters, New York †	253	72	0.3
VI. Industrial			
Textile mills			
Dusty (carding, etc.)	17	2,425	0.0
Settled (spinning, etc.)	17	261	0.0
Humidified (weaving, etc.)	21	275	0.0
VII. Transportation			
Railway cars, air conditioned			
Without ultra-violet lights	16	440	4.3
With ultra-violet lights	9	127	0.5
Subway cars, New York †	290	192	0.85

* The samples were approximately 10 cu. ft., but the accuracy of sampling and isolation by various workers does not warrant more precise analysis.

† These figures are computed from Pincus and Stern, *A.J.P.H.*, 27:321, 1937.

can be justified by the bacterial purity indicated by the tests. A study of the sanitary ventilation of Chapple infant incubators [10] supplied with clean outside air clearly shows the sanitary superiority of the air within the incubators over that of the wards in which they were placed.

Qualitative Differentiation by State of Suspension—Interpreted in conjunction with other observations much valuable information upon the quality of the contamination may sometimes be derived from bacterial counts. In the study of textile mill atmospheres [11] the ratio of bacterial concentration as determined by the centrifuge to plate settling count proved of great value in distinguishing between bacterial contamination derived from dusty operations and that contributed by humidification with polluted water. The differentiation of contamination derived from such widely different sources is necessary to a proper hygienic evaluation of the bacterial content of the atmospheres.

Settling and Sedimentation—Quite apart from such qualitative sanitary distinction the settling rate of bacteria-laden particles as determined by the ratio of plate count to that obtained by the centrifuge provides the key for interpreting the flight range of air-borne infection in space and time. Sedimentation in still rooms is an important factor in removing dust from the air.[12] The accumulation of settled infected dust [13] may, however, provide a dangerous source of reinfection. In operating rooms, preparations just preceding an operation may stir up accumulations, deposited over a long quiescent period between use and concentrate infection from distant parts of a hospital.

Particle Size and Purification—The coefficient of fineness, derivable from settling velocity,[11] may be a factor in the efficiency of purification devices which depends upon the physical characteristics of the particles. Such distinction between bacteria introduced into air by evaporation of salivary droplets and bacteria raised as dust by processes of attrition may be of vital importance in the hygienic interpretation of bacterial tubes. This is well illustrated in efficiency tests of a railway car installation of ultra-violet lights which showed a much higher effectiveness against nasopharyngeal organisms than against the wild varieties enclosed in dust raised by activity within the car.

INDICES OF NASOPHARYNGEAL CONTAMINATION

The hygienic significance of breathing microörganisms fresh from the respiratory passages of others cannot be ignored. The numbers of streptococci characteristic of the nasopharynx indicate a hazard of respiratory infection and have a sanitary significance comparable with the presence of *Escherichia coli* in drinking water.[14] Examination of averages in Table I shows how these numbers vary with the condition of occupancy.

Specific Infectivity—Fluctuations dependent upon sneezing are indicated in experiments from which it is estimated that several thousand nasopharyngeal streptococci per sneeze are contributed to the atmosphere. The sneeze thus almost seems to be a provision of nature for the survival of nasopharyngeal parasites. Even where the manifestations of a disease do not provide for the wide auto-dissemination of the infection through air it has been observed that an outbreak of colds will be followed by the rapid spread of contagion.[15, 30] Sneezing induced by pollens might conceivably facilitate the spread of nasopharyngeal infection, and has indeed been suggested as a means by which the unseasonable spread of poliomyelitis is aided.[16]

These experimental results are borne

out by the field observations of Huddleston and Hull[17]:

During February, 1919, there existed in the Army of Occupation what amounted to an epidemic of severe "colds" with extremely bad coughs and sore throats. Pneumonia cases were numerous. The first experiment was conducted on February 23. . . .

It will be seen that in one minute an average of 82 organisms settled on the plates, and in five minutes, 151 organisms. . . .

In picking colonies indiscriminately from the incubated plates four type IV pneumococci were found, and many hemolytic and non-hemolytic streptococci, with numerous staphylococci and Gram-negative and Gram-positive diplococci. . . .

Eight days later (March 3), the experiment was repeated. . . .

By the first of March the epidemic had practically cleared up. . . .

The details of operation were identical in every particular—the same medium being used and the same methods. On the plates exposed 1 minute and 5 minutes the organisms found were extremely few in number. On the plates exposed 10 minutes an average of 16 colonies was counted. Among these, molds and staphylococci predominated; no pneumococci were found; 16 per cent of the total number of colonies present were streptococci, which showed partial but not complete hemolysis (alpha type).

This great reduction from 82 organisms in 1 minute to 16 organisms in 10 minutes, which settled on the plates directly corresponded to the falling off of the epidemic. In either case, however, a man sitting through a performance of 1½ to 2 hours would inhale enough pathogenic organisms to give him any respiratory disease which might prevail among those sitting about him, provided he did not possess some natural or acquired resistance.

The prevailing organism present in the respiratory passages of men admitted to the hospital at this time was *Streptococcus hemolyticus*.

Sanitary Indices of Pollution Load—The impression gained from inspection of Table I that the numbers of alpha streptococci in the atmospheres we breathe conform in a general way to the density of occupation and the degree of air confinement, is strengthened by a more detailed analysis of the New York figures.[18] Thus in reporting on the 6 schools selected in the New York study, the authors state:

Schools numbers 1 to 3 have higher average numbers of streptococci per cu. ft. of air for all samples and for positive samples, as well as a greater percentage of positive samples, than do schools 4 to 6.

Schools 1 and 2 are two of the oldest in the city and are in the lower east side. They are of definitely inferior construction, contain small rooms, and are difficult to keep clean, number 1 being the poorer of the two. It may also be of interest that the children are of the lowest economic group in the city, and come from a health area which shows a high incidence of reportable communicable disease. Schools 5 and 6, the two high schools in the group, are located in the upper middle west side. While of more modern construction than the first two schools they cannot be called new. They are of more suitable design than the former, however, since they have large rooms, large windows, and high ceilings.

With respect to degree of occupancy they state:

The values for the average number of streptococci per positive sample for all schools indicate that occupied assembly rooms had most alpha streptococci, followed by occupied classrooms, corridors, just vacated classrooms, vacant assembly rooms, and vacant classrooms in the order named.

Table II likewise shows a relationship between passenger load of a railway car and the numbers of alpha streptococci present in the air. The ratio of streptococci count to passenger load for every moment in time obviously is not constant, but varies with activity of the passengers contributing to the atmosphere.

Hygienic interpretation of these results in the absence of extensive epidemiologic correlation can be based only upon general sanitary principles gained primarily from long experience with water supplies. The ingestion of intestinal organisms indicated by the presence of *Escherichia coli* in one-tenth of the volume of water consumed per 24 hours per person approximates a limit of safety set by the U. S. Treasury

TABLE II

Relation Between Passenger Load and Bacterial Content of Air of Railway Car
(With and without ultra-violet light in air-conditioner)

Tube Number	Sampling Time (in Minutes)	Number of Passengers	Total Bacteria	Alpha Streptococci
		Ultra-Violet Lights Off		
1	20	65	209	0
2	10	..	1,022	9 plus
3	20	69	1,324	5 plus
4	10	..	466	8 plus
5	20	82	418	15 plus
6	10	..	1,324	7 plus
7	20	75	860	23
8	10	..	372	4
9	20	52	929	5
10	10	..	209	2
11	20	48	372	6
12	10	..	442	1
13	20	30	1,069	3
14	10	16	325	2
15	20	1	232	0
16	10	6	232	1
		Ultra-Violet Lights On		
17	20	15	349	2
18	20	28	256	3
19	20	39	232	0
20	20	..	139	0
21	20	43	302	0
22	20	..	302	1
23	20	48	232	0
24	20	55	186	0
25	20	55	279	1

Standard [19] for drinking water. The inhalation of more than 10 times as many respiratory organisms in the same period is indicated by the presence of three alpha streptococci per sample of 10 cu. ft.

EPIDEMIOLOGIC FACTORS

Sound sanitary principles appropriate to ingested infection from drinking water cannot be applied arbitrarily to an inhalation theory of the spread of respiratory disease without confirmation of the underlying assumptions. They may, however, lead to more fruitful hypotheses than the smug logic familiar to the early advocates of pure water that the air breathed " all one's life " cannot help to explain the universality of respiratory infection. Where the *droplet* theory has led only to a hopeless attitude toward the sanitary control of respiratory disease, a theory of airborne infection, based upon the wide dissemination of *droplet nuclei* through occupied spaces,[20] promises such sanitary methods for building up community resistance against the spread of this important class of infections as have proved so successful in controlling spread of insect-borne and intestinal disease.

Topley and Wilson [21] clearly indiccate the potentialities of increasing community resistance by control of the sanitary factors involved in the spread of infection.

> The herd, like each of its members, has a characteristic structure; and this structure, from our present point of view, includes

not only the hosts belonging to the herd species, and their spatial relationships to one another, but the presence and distribution of alternative animal hosts and possible insect vectors of infection, as well as all those environmental factors that favour or inhibit the spread of infection from host to host. This herd structure, apart altogether from the susceptibility or resistance of the individual hosts, may play a decisive part in the immunity of the herd as such. A herd may be immune to a particular disease—in the logical sense that it will resist the introduction of infection from without—although each of its members is fully susceptible, and would fall an easy victim if he strayed to a herd with a structure that allowed an endemic prevalence of the disease in question. In this sense the English herd is immune to plague; because the association of man, the rat and the flea is not now of a kind to allow spread along natural routes. It is probably immune to cholera, as the result of an adequate system of water purification. It is not—nor does it seem likely to become—immune to any of those diseases that are spread by droplet infection. It would take us altogether beyond our present scope to consider the known or problematical effects on herd resistance of such changes in environmental conditions; but we may at least note that many of the most striking successes of preventive medicine have been attained by altering herd structure without inducing any increased resistance in its individual members. By attacking insect vectors of infection, such as the mosquito, by preventing the frequent passage of bacteria from one person's intestine to another person's mouth by way of water and food, and by a general improvement in environmental conditions, we have succeeded in eliminating, or reducing to negligible proportions, diseases that formerly took a heavy toll of lives, and still take that toll in areas where such measures are not applied.

Substitution of the words "community resistance" for "herd immunity" would better contrast sanitary resistance to the spread of infection through a community with that conferred upon a herd by the specific immunization of a portion of its members.

If bacteriologic interpretations are corroborated by epidemiologic experience, sanitary ventilation, based upon a theory of air-borne infection by droplet nuclei, promises to become an important factor in public health.

SPREAD OF INFECTION THROUGH AGGREGATIONS

The hypothesis that contagion may be spread through the common occupancy of semi-confined atmospheres defines an epidemiologic pattern in terms of sanitary ventilation. Though sanitary and epidemiologic indices of ventilation have never been specifically correlated, extensive data on the spread of respiratory infection through various human aggregations sharing common atmospheres have accumulated. General correlation between types of ventilation characterizing these types of aggregation and epidemiologic indices derived from these studies reveals the consistency between our interpretation of the bacteriologic measure of air infection and the spread of respiratory disease.

Continuous Aggregations—The spread of disease through semi-confined atmospheres is not always an obvious phenomenon. Since the individual normally shuttles from aggregation to aggregation, it is generally impossible to distinguish the atmosphere within which an infection is contracted. Even where respiratory infections are known to be contracted within a continuous aggregation of individuals, only under special circumstances can sources other than air be entirely eliminated. In a careful study of the spread of infection in the Infants' Hospital, Boston, McKhann and his associates [22] report 134 acute respiratory infections developing among 1,455 admissions during 1935 and 1936. Converted on the basis of the time of residence, this attack rate becomes an annual rate corresponding to *epidemic* spread of water-borne intestinal infection (more than 100,000 cases per annum per 100,000 population at risk). In a further analysis of these data,[9] they conclude that contact infection, droplet infection, and droplet nuclei infection are all operative within the hospital, and that a clear distinction must be made in the proportion of infections attributable to each mode of spread in an appraisal of methods of control. He distinguishes the principles of control applicable to each mode of spread, and will later report upon experimental control measures. He is extending to cubicle isolation the principle of an ultra-violet light barrier against droplet nuclei infection, inaugurated nearly 2 years ago in a corridor. He also remarks upon the striking reduction of respiratory infections in the premature ward,[8] correlative with a demonstrated reduction in bacterial contamination, consequent upon the installation of an independent outside air supply (see Table I).

By means of the newer laboratory technics which permit cross-infections to be traced as both clinical cases and subclinical infections, we are coming to realize how much more numerous they are than had been supposed. Clinical cases of certain nasopharyngeal infections may constitute, according to advanced work, particularly in England, mere outcroppings of epidemic strata of subclinical infection which can be located by the newer technics of bacterial typing.[23] By such procedures the latent image of the mode of spread of nasopharyngeal infection, manifest in such diseases as measles and influenza and deducible from epidemiologic studies of age incidence and immunity tests,[24] may be developed.

Intermittent Aggregations — The spread of infection through intermittent aggregations may often be traced by the characteristics of the disease. The incubation period in some of the common infectious diseases of childhood, where lasting immunity is conferred, links primary with secondary cases. Every "contagious" case is secondary in some one aggregation, though it may or may not be a primary to other cases in that or other aggregations. The number of secondaries thus exceeds the number of primaries except in the limiting case of perfect endemicity where the number of secondaries equals the number of primaries and there is no change in the rate of incidence. The sharper the epidemic, the more do secondaries exceed the primaries.

The spread of contagion through various types of aggregations describes the progress of an epidemic through the community. It is evident from Wilson's intensive study [25] of the epidemiology of measles in Providence that the 6 to 7 year old group of children provides the stratum of the population in which lies the reservoir of measles from which family primaries are drawn. This is true whether a younger or an older child is the primary in the family. Thus an elder child passing through this stratum without becoming a family primary is more likely to become later a secondary to a younger primary drawn from this stratum. The ratios of secondaries to primaries in the aggregations constituting this reservoir may vary independently from the ratios of secondaries to primaries in the family aggregations. Epidemic surges, therefore, arise from the interlocking of these various aggregations forming the knots in the vast network of contagion.

The family has been a favorite aggregation for the study of these phenomena:

> One of the most characteristic features in the epidemiology of the common acute communicable diseases is the grouping of cases in time and space; and this is especially apt to be noted in the group which constitutes a household, people in close contact with each other, sharing a common environment, mostly of close kinship, and usually under the eye of at least one medical or lay observer whose observation encompasses the whole group.

Thus did Frost [26] introduce a discussion of "Familial Aggregations of Infectious Diseases" based upon Chapin's classic work on secondary attack rates. In 1925 Chapin showed that 88.3 per cent of presumably susceptible children of ages 1 to 5 contracted measles when a case was introduced into the home.[27] He concluded further:

Scarlet fever, consequently, is in reality much more contagious than the diagram would indicate, for the number of non-immunes is less than formerly assumed. It therefore seems probable that the greater contagiousness of measles, as suggested by Diagram III, is to a considerable extent apparent only. . . . Indeed, it is possible that diphtheria might be proved to be not so very much less contagious than measles. . . . We have no data in Providence bearing on the contagiousness of smallpox, but certain facts, from other places indicate that it approaches measles in this respect.

Dyer [28] quotes Rist and Weiss and Zingher and others who—

have noted the tendency of children of the same family to give similar reactions to the Schick test, and that in case of variations, as a rule, the younger children have shown positive reactions and the older negative, the reverse of this being very rare.

In response to the Dick test, Dyer's own results among 263 families of two or more children showed that: (1) in 151 instances all were Dick positive; (2) in 30 instances all were Dick negative; (3) in 41 instances younger children were positive, older were negative; (4) in 25 instances younger children were negative and older children were positive; (5) in 16 instances in family groups of three or more children, other combinations were shown. That is to say, in only 15 per cent of the 263 families was a younger child immune and an older child susceptible.

Similar phenomena with respect to tuberculosis among families is reported by Opie and McPhedran [29]:

When latent tuberculosis is taken into consideration, tuberculosis exhibits the characters of a contagious disease and affects all children of households within which some member, suffering with tuberculosis, scatters tubercle bacilli.

As regards the spread of homologous types of pneumococci among family contacts, the Advisory Committee on Prevention of Pneumonia Mortality state [30]:

The findings obtained in a few studies of a small number of families suggest that when pneumonia due to one of the more virulent types, for instance Type I, occurs in an individual, about 20 per cent of the other members of the patient's family are also carrying that same type of organism in their noses or throats. Where acute upper respiratory infections, such as colds, are prevalent among the family contacts, the incidence of homologous type carriers may approach 70 or 80 per cent.

The interesting epidemiologic fact [31] that the average age at which first-born children contract clinical poliomyelitis is greater than second-born, second-born greater than third, etc., suggests simultaneity of infection, clinical or subclinical, within the family. The family pattern of subclinical infection would, therefore, be similar to the family pattern of clinical infection in the case of measles. The epidemiologic study of immunity by birth order in a family gives such distribution of age incidence as would follow the assumption that the introduction of an infection into a family leaves the exposed members of the family immune if they do not contract a clinical case of disease.

Time of Exposure—It appears from such experience that a susceptible child breathing the air in a home harboring a contagious case seldom escapes infection, either manifest or latent. Here the time element in exposure (early observed by Denny [32]) characterizes airborne infection. Both the case and the victim continuously breathe the same atmosphere for extended periods of time. In schools, on the other hand, the time of exposure is markedly reduced by the prompt removal of detected cases. Boarding schools in this respect are intermediate between day schools and homes. In a very thorough

FIGURE I—Sanitary ventilation by means of bactericidal radiation in new building of the Cradle, Evanston, Ill. Ultra-violet light barriers separate cubicles from corridor. In right tier of cubicles, ultra-violet light curtains also replace alternate solid partitions.

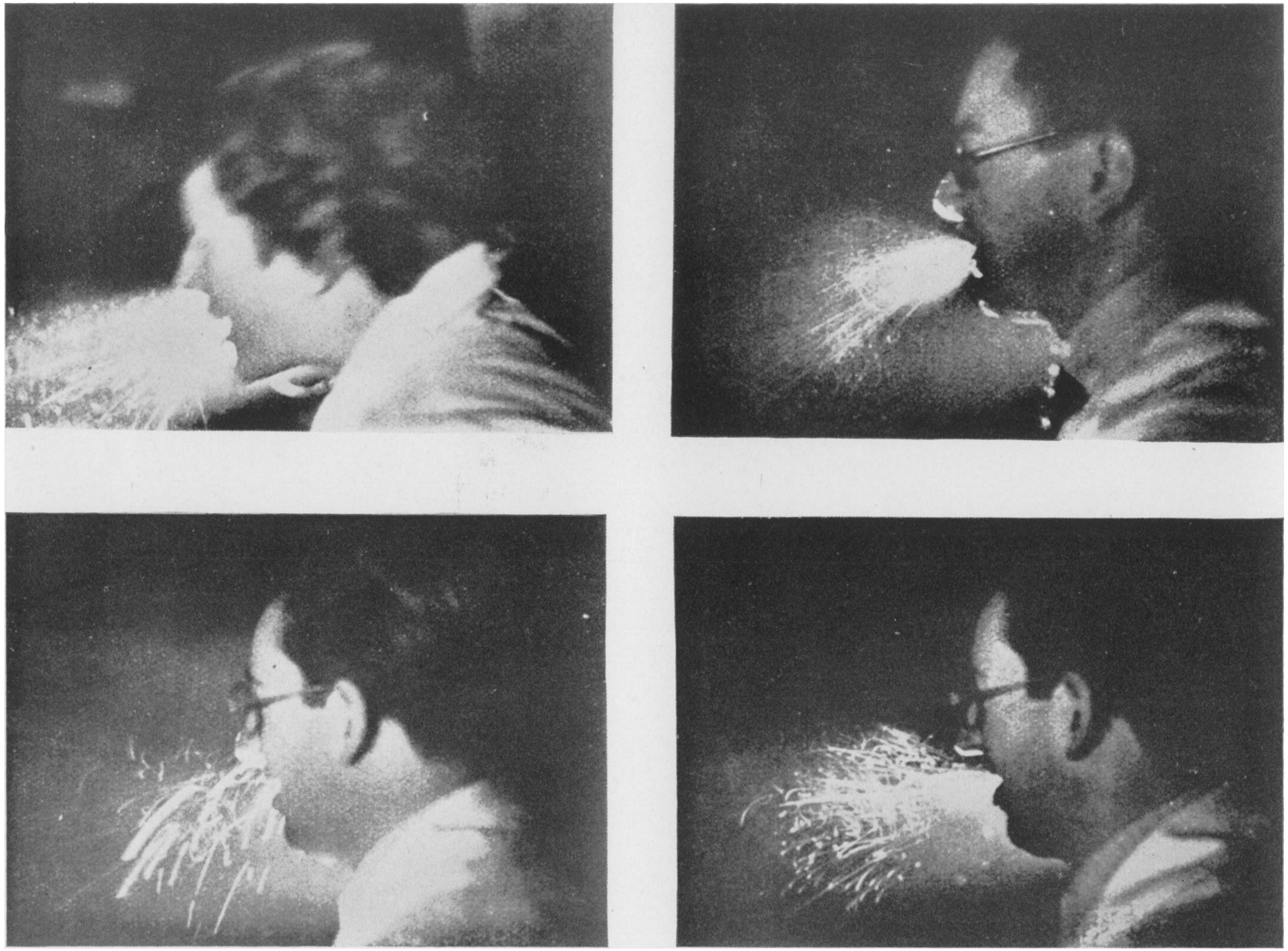

Figure II—Droplet nuclei (contrasted with Flügge droplets) photographed by the Tyndall effect. Upper left, sneezing; upper right, pronouncing the letter "p"; lower left and right, pronouncing the letter "t." (Taken from F. Weyrauch and J. Rzymkowski. Photographien zur Tröpfcheninfektion. *Ztschr. f. Hyg. u. Infektionskr.*, 120:444, 1938.)

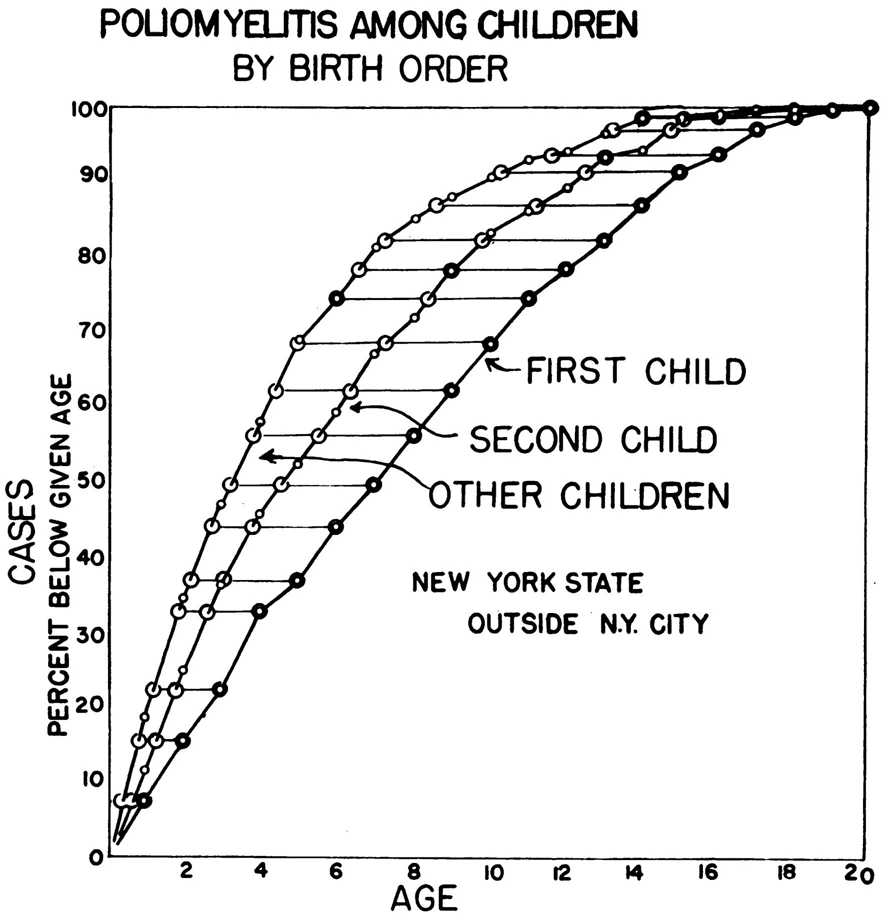

FIGURE III—Age incidence of poliomyelitis by birth order. New York State (exclusive of New York City), 1926–1930. (Data obtained through the courtesy of Dr. E. S. Godfrey.)

study of "Epidemics in Schools" recently issued by the Medical Research Council of Great Britain (Special Report Series No. 227 [33]) the records over 5 years show an average of 14.2 cases for each contagion * introduced into 26 boarding schools and 3.3 cases for each contagion introduced into 2 day schools. The schools were broadly comparable in size and age-distribution and the probability that these figures reflect differences in exposure-time rather than differences in numbers or immunity-composition of the subjects is borne out by the familiar studies of Dudley [34] on the different attack rates of day and boarding pupils.

Intensity of Infection—Data on the intensity of infection so clearly emphasized by Glover [15] are also provided in the same study. An average of 17.2 cases for each contagion introduced into 17 boarding schools for boys, as against an average of 9.1 cases per introduced contagion in 9 girls' boarding schools (in spite of greater degree of reported immunity among the boys) may indicate the greater congestion in

* The word "contagion" is here used in a restricted sense. It refers to the common childhood contagions: measles, German measles, mumps, chicken pox, whooping cough, scarlet fever and diphtheria.

boys' dormitories than in the girls' houses. In the boys' day school, on the other hand, where conditions for the spread of contagion are more comparable, 2.8 cases as against 3.8 cases in the girls' day school per introduced contagion, probably also indicate greater immunity among the boys.

Could it be that differences in climate and method of ventilating homes in England and New England may help to explain the differences in the secondary attack rates in St. Pancras and in Providence, as observed by Wilson [25]:

Moreover, Greenwood's data taken from Stocks show secondary attack rates of 25 to 35 per cent with all children under 10 years of age left in whether immune or not and of 45 to 50 per cent with the immunes (those who had had measles) rejected, whereas we find in Providence secondary attack rates on susceptibles under 10 running 75 to 80 per cent, and on all children under 10 from 60 to 65 per cent. Apparently, then, measles is far less infectious under conditions of family life in St. Pancras than in Providence.

Could the conditions which account for one escape in a family so favor other susceptibles as to depress the secondary attack rate as found by Wilson [25]:

If next we look to the single primary families which have one specified susceptible escape, we find the secondary attack rate on the other susceptible to be 55.6 ± 4.6, and thus the presence of an escape lowers the secondary attack rate more than the presence of an immune.

Could the seasonal difference in secondary attack rates in Detroit, as reported by Top,[35] also be explained on the basis of greater confinement of children in air more confined from January through April, causing a greater intensity of infection during those months over the preceding and following months, as shown in Table III.

TABLE III

(Detroit, 1935, Top)

Attack Rates among Susceptible Contacts by Age and Month

Month	*Number Contacts*	*Number Cases*	*Attack Rates*
January	38	33	86.8
February	136	120	88.2
March	589	511	86.8
April	620	532	85.8
May	196	156	79.6
June	45	26	57.8
July	6	..	(0.0)
August	..	..	(...)
September	3	2	(66.7)
Totals	1,633	1,380	84.6

What interrupted the "seasonally interrupted" epidemic in Providence, also referred to by Wilson [25]:

The course of measles in Providence 1929–1934 was characterized by a low incidence in all years but 1931 and 1932 and a major epidemic in those years. . . . The course in 1931 consisted of a moderate epidemic in the late spring falling to a score of cases in September and a sharp rise to epidemic proportions. For this reason we consider that the behavior of measles in 1931–1932 may properly be characterized as a major epidemic seasonally interrupted rather than as two epidemics, one in the late spring of 1931 followed by another in the fall of 1931 and winter of 1932. Hence we shall speak of 1931 as the first and 1932 as the second part of the great 1931–1932 epidemic which contained about six-sevenths of all the measles in the 6 year period 1929–1934. The ratio of secondary to primary cases changes from year to year by more than can be attributed to chance; it is quite high in 1931 and decidedly low in 1932. The ratio of primaries to families also changes being apparently low in the years in which there is little measles—the difference between the figures for 1931 and for 1930 being not significant.

Multiple Exposures—Such a prevalence of disease as subjects a case to multiple infections in different aggregations complicates the determination of the degree of exposure in any one aggregation. Incidence within an aggregation becomes more truly a measure of susceptibility than of degree of exposure to infection for such diseases as the common cold, where lasting immunity is not conferred, where several attacks per person per season may occur, where adults as well as children harbor the infection. Thus Wilder [36] observed that, in the Germantown Friends School, the epidemiologic pattern of upper respiratory infections differs from the pattern of childhood contagions. The incidence of colds is remarkably uniform from year to year, and constant for classes and groups of individuals. Our own analysis of Wilder's data convinces us that school exposure does not ordinarily determine incidence of colds within day schools: absences from colds on Wednesday, Thursday, and Friday account for no more than their proportionate share of the weekly incidence. Assuming broad infection spread (i.e., more than one infection per cold), prevention of colds would depend upon the prevention of multiple infections, for not until the last remaining infection was prevented would a cold be avoided. Studies of methods for the prevention of colds will require isolated aggregations, unexposed to a variety of outside sources, where spread within the aggregation can be measured.

DIFFERENTIATION OF EPIDEMIOLOGIC PATTERNS

The demonstration of an epidemiologic pattern of spread of contagion through aggregations sharing common atmospheres, even though consistent with a demonstrated mechanism for interchange of nasopharyngeal organisms in breathing the common air supply, does not of itself necessarily demonstrate air-borne disease. High correlation between the common occupancy of semi-enclosed atmospheres with other opportunities for infection might lead to similar phenomena.

Close association within aggregations sharing a common air supply also facilitates spread of infection by Flügge droplets and contact. Separation of these modes of spread can be made only on the basis of more refined analysis of the original data than is possible with records studied and reported through the medium of the droplet or contact theories. The degree of proximity in time and space required by these hypotheses will not, however, explain many well established examples of the spread of contagion.

Exclusion of other Modes of Spread—Thus in the classic outbreak of psittacosis in the Hygienic Laboratory, reported by McCoy,[37] both droplets and contact could be rigidly eliminated. Stimson [38] states:

> During the course of the experiments, which had been undertaken with what appeared to be ample precautions, an outbreak occurred among the personnel at the National Institute of Health, involving 11 persons, 1 of whom died. This would seem to indicate an almost incredible diffusibility of the infection through the air, since some of the victims had not been nearer to the rooms in which the animals were kept behind moist curtains, and with troughs of disinfectant at the doorways, than to pass to and occupy rooms in distant parts of the large buildings. This has led to the assumption that the virus may be spread by the "powder down" thrown off by parrots, which seems to have a diffusibility comparable to the pollens.

Seldom in epidemiology can the factors of droplets and contact be so completely eliminated. In experimental work on animals, however, these variables can be controlled. Thus Dunkin and Laidlaw,[39] in reporting on the spread of dog distempter through ferret and dog aggregations in which these factors were carefully excluded, state:

> Control dogs cannot be kept free from disease in the experimental house, though kept in separate cubicles and the fullest antiseptic precautions maintained by the attendants to avoid carrying infection from one animal to the other. The dogs were not confined in Topley cages, and so the barrier against spread of infection in their case was less perfect; but we are convinced that aerial spread can and does occur in closed buildings, and we have now abandoned experimental work with dogs in confined spaces and work in the open air.

We pointed out that in the case of ferrets there was practically conclusive evidence of air spread of the virus of dog-distemper in confined spaces over short distances. Our experience with dogs is in entire harmony with this conclusion, as we found that it was impossible to keep a control dog in one cubicle of the experimental house when infected dogs inhabited the adjacent cubicles. We were compelled to abandon this method of experiment and substituted a system which is in large measure successful. It consists in keeping the experimental dogs in kennels and small runs scattered about the grounds around the laboratory buildings. Each kennel has a small run enclosed by fencing and wire netting, and is separate from its nearest neighbour by a distance of 15 to 20 yards. We thus rely on dilution by the external air to prevent the spread of infection from one cage kennel to its neighbour. The attendants who attend to the animals wear the rubber armour which has previously been described, and between each visit to a cage kennel have this armour washed down with lysol. All excreta and all food and drinking vessels are disinfected with lysol every day. The dogs are fed on boiled biscuit and boiled horse meat and bones.

Direct infection of the lung by intranasal instillation (under anesthesia) is now a recognized laboratory procedure. Infection through the respiratory tract by dust containing tubercle bacilli has been reported frequently and has become a routine procedure for experimentally infecting rabbits at the Henry Phipps Institute.[40] Inhalation experiments have also shown that animals can be experimentally infected by breathing air in a chamber which has been sprayed with pathogenic microörganisms.[41]

More recently we have devised a technic for infecting animals in air conditioned chambers supplied with air infected with " droplet nuclei " outside of the chamber. No objection can be raised to the conclusion that these were truly air-borne, for they had been carried in the air stream over long distances. The bacterial concentration of the air was quantitatively controlled, and a relationship demonstrated between the quantity of infection so breathed and the mortality of the animals. Elaboration of this equipment will permit exposures of large numbers of animals over long periods of time to small concentrations of infection and so imitate the conditions of ventilation in our habitations. Experimental ventilation will bridge the bacteriologic deductions in the first part of this paper with the epidemiologic observations considered in the second part.

Determination of Pattern by Ecologic Factors—Exclusion of other than one mode of spread is not necessary to distinguish an epidemic pattern. Plague in warm climates disseminated by rodents, insects, contact, and droplets may become suddenly transformed into a pneumonic or air-borne pattern better explained by droplet nuclei under conditions of crowding within enclosed spaces during cold weather. Thus Strong and Teague,[42] after showing experimentally that the period of infectivity of pneumonic plague coincides with the coughing phase of the disease in which the air becomes infected, show:

. . . from the study of human lesions and those produced experimentally in animals it would appear that endemic plague pneumonia results from inhalation, the primary point of infection being the bronchi.[43]

They further state that

there is a greater tendency for the disease to spread in cold climates than in warm ones.

In harmony with the above ideas, we find that the only great epidemic of pneumonic plague of modern times occurred in Manchuria during the winter of 1910 to 1911, when the atmospheric temperature was many degrees below zero Centigrade. The disease spread with amazing rapidity. Furthermore, although during the past fifteen years there have been millions of plague cases in India and 2 to 5 per cent of these have been cases of plague pneumonia, yet this form of the disease has not assumed epidemic proportions. The largest epidemic of pneumonic plague in India (1,400 deaths) occurred in Kashmir in northern India at an elevation of 1,524 meters above the sea level during very cold weather.[44]

Strong, in 1935,[45] summarizing his experiences, states:

Thus it was shown that while the germ of primary pneumonic plague is essentially the same as the organism of bubonic plague (with the exception of exhibiting a uniformly great virulence throughout the epidemic), the portal of entry of the microörganism is different from that in bubonic plague; and that in an epidemic of primary pneumonic plague, rats and fleas play no part in the transmission of the disease, the infection occurring directly from man to man by the droplet method of infection in a somewhat similar manner as in influenza. Overcrowding of the inhabitants in midwinter in small huts (sometimes thirty to forty people in one room) with very little ventilation was an important factor in the spread of the disease in Manchuria.

In the spread of respiratory diseases, the recent investigations of Wells and Stone (1934) upon air-borne infections are of interest, in which they point out the importance of dried infected droplet nuclei derived from droplets less than one-tenth of a millimeter in diameter.

Velocity of Spread—Perhaps the most characteristic feature of the air-borne pattern is the velocity of epidemic spread of infection,[46] implicit in the droplet nuclei hypothesis. The spread of influenza through army barracks during the World War could not, we believe, have been so swift as that described by Opie, Blake, Freeman, Small and Rivers[47] if it travelled by steps limited in space to the proximity demanded by the droplet or contact theory and separated in time by the necessary incubation period.

The most striking feature of the epidemic was the extremely rapid spread of the infection throughout the camp. Starting September 22 in a regimental area situated in the extreme southwestern corner of the camp, the disease had within 4 days appeared throughout the camp proper, and 4 days later appeared in two outlying encampments, situated respectively 1 mile north and 3 miles east of the main camp.

No single organization escaped the infection, and during the 30 days from September 20, 23.3 per cent of the total population of the camp suffered from the disease. The figures given herewith are based on a detailed study of 11,725 cases occurring between September 20 and October 14, and comprise practically the whole of the epidemic. . . .

Infection with hemolytic streptococci may spread as an epidemic through the pneumonia wards of a hospital. A single patient with streptococcus pneumonia is a source of grave danger to every patient in the same ward. Superimposed infection with hemolytic streptococci increases the mortality of pneumonia so that it may reach from 50 to 100 per cent of all patients with pneumonia. . . .

There seems little reason to doubt that the incidence of pneumonia and the death rate of that which occurs might be greatly diminished by preventing all overcrowding of new recruits in barracks and by providing hospital facilities in considerable excess of the routine demand.

Hospital epidemics of streptococcus pneumonia will be prevented when medical officers have that dread of the disease—comparable to our dread of puerperal fever—which is inevitable when its characters are accurately understood.

Transition from Contact to Air-borne Pattern—In this sense measles may or may not assume an air-borne pattern. The School Epidemics Committee report[33] states:

It is a remarkable fact that quite a high proportion of outbreaks of infectious disease did not spread at all. . . .

It will be noted that on the average about 30 per cent of all outbreaks among the boys, and about 40 per cent among the girls, were thus curtailed (that is, limited to one case, though girls were more susceptible than boys). . . .

When introduced into a school, measles may or may not spread, quite irrespective of the number of susceptibles in the population, but it is more likely than any other disease to assume epidemic proportions, at any rate among the boys. . . .

We have other examples of measles gaining access to a school early in the term, hanging fire for a few weeks, and then causing a large epidemic.

A study of the figures in this report will reveal the fact that over one-half of the cases of measles resulted from less than one-fifth of the introductions of the contagion, and that over 90 per cent of the cases resulted from less than one-half of the introductions.

Some factor besides the virulence of the virus or the resistance of the host must be involved in these wide differences in the velocity of spread of a disease which is considered so highly contagious.

The transition from a contact to an air-borne pattern of spread following the introduction of independent means of dissemination of the virus through air is described by Stallybrass.[15]

> In mumps the author has noticed that the disease sometimes progresses slowly in a school until an outbreak of an epidemic catarrh causes much sneezing, coughing, and spluttering. The mumps epidemic now progresses rapidly. The sudden outbreak marks the transition from contagion to droplet infection and not the alteration of the virus. It has repeatedly been noticed that return cases of scarlet fever follow an attack of a cold in the infecting case; a cold not only increases the amount of mucus discharged into the outer world, but also produces sneezing and coughing; it may also determine a relapse of otorrhoea.

Although Stallybrass uses the words "contagion" and "droplet infection" in a sense differing from that used in this paper (showing, in fact, the confusion in terms applied to the mode of spread of nasopharyngeal infection), there can be little doubt that he recognizes a distinction between the contact and air-borne patterns.

SUMMARY AND CONCLUSION

"Measurement of Sanitary Ventilation" described a method of determining the rate of *removal* of microörganisms from semi-confined atmospheres, with special reference to air disinfection by means of ultra-violet light. An example of the practical usefulness of this method is offered by an experimental study and design of isolation cubicles in which ultra-violet light screens replace solid partitions or where a curtain of light is dropped, continuous with an irradiated reservoir or "ceiling" above the eye level into which any solid cubicle partitions project.

The present paper considers methods of determining the rate of *addition* of microörganisms to semi-confined atmospheres in defining the hazards from air infection and means for the avoidance of such infection.

Sanitary interpretation of analyses of some two thousand samples of air supplied to various human aggregations reveals the consistency between deductions from a theory of air-borne infection, based upon bacteriologic experiments, and epidemiologic evidence of the spread of contagions through aggregations sharing a common air supply. Air-borne infection of animals exposed to quantitative dosage in experimental ventilation further reflects this consistency.

Some few outstanding examples are selected to illustrate an epidemic pattern, fogged by the droplet theory, but clear when viewed through the hypothesis of nuclei from the evaporated droplets. Such a pattern of air-borne spread by droplet nuclei accurately describes the epidemic spread of respiratory infection among individuals aggregated within atmospheres in some degree confined, and can be related to the familiar pattern of epidemic spread of intestinal infection through the medium of water, food, or milk.

Both intestinal and respiratory infection are undoubtedly spread *endemically* by intimate personal contact. The simultaneity or swiftness of *epidemic* spread of both, however, can be better explained by common source media. Each describes its own epidemic pattern true to the physical and biological factors which govern the respective media, just as the patterns of both differ from the pattern of insect spread of disease.

Discovery of the vehicles of transmission of ingested intestinal infection led to successful sanitary measures of control. Recognition of a vehicle of contagion may likewise suggest the means of preventing epidemic respiratory infection.

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Public Health Administration Program

TODAY public health administration is questioning every form of disease, physical and mental; its thought is not limited to the modest possibilities of the clinic, the classroom, or the health leaflet or poster; it demands complete medical service and plans widespread popular education in hygiene as a matter of course, but these activities have been reduced to minor rank in a larger and more significant program. Public health administration now aims to control all environmental factors which affect health. The stupendous task which it appears to have set for itself is not quite frankly avowed, but this task, as I apprehend it, is to define and to apply through social administration a physiologically sound standard of living. Public health administration proposes, in effect, a benevolent dictatorship in the name of health, thus applying in a drastic and wholly unexpected form, the familiar saying that the public health is a concern of government.—*S. S. Goldwater, M.D.*, at dedication exercises, Memorial Hospital, New York, June 14, 1939.